Improvement of Reliability Indices in a Micro-grid System involving Renewable Generation and Energy Storage

A Thesis

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Abstract

Integrating renewable energy sources is important to policy-makers worldwide, especially as the depletion of traditional energy sources and the declining health of the environment continue to be of critical concern. As the installation costs of renewable generation decrease, the incorporation of these sources into the grid is becoming more attractive and feasible. However, in order for renewable generation to be incorporated on a large scale, utilities must be able to guarantee that customers receive adequate and quality power, constituting a reliable system. Thus, ensuring the reliability of a grid system that includes sources of generation with low predictability and high variability, such as wind and solar, is investigated. Energy storage is shown to help eliminate or reduce the load demand that must be met by renewable generation and supply power when renewable generation is unavailable or insufficient, thereby increasing the reliability of the system. With increased research focusing on implementing a smart grid, this study implements a small-scale system called a micro-grid, which has the capability to disconnect from the main grid. This study focuses on a micro-grid in the islanding mode. A mixed integer optimization model of the problem is developed that maximizes the reliability of the micro-grid system by determining the number of critical and non-critical loads that can be satisfied at each time step. The maximization of the number of loads is constrained by the available renewable and stored generation in the system at each specific time step. The generation from wind and solar is estimated using a Weibull and Beta distribution respectively. The software Gurobi with CVX using MATLAB and the IEEE-9 bus system is used to solve the optimization problem and analyze the results. It is shown in this study that the System Average Interruption Frequency Index of the system improves with the incorporation of energy storage into the micro-grid. A specific case study showing the results from this research is demonstrated on a small-scale system in Honduras that includes wind and solar generation. This study shows the potential to improve the feasibility of renewable energy sources in the grid system by using energy storage, thereby lowering emissions in electricity generation.

Dedicated to my family, especially my parents, my friends, and my co-researchers for their endless support

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

Integrating renewable energy sources is important to policy makers world-wide, especially as the concerns for the environment heighten and the depletion of traditional energy sources increases [5]. Despite these things, the demand for energy continues to rise [5]. According to [5], electrical energy makes up 12% of the total energy processed by humanity, and it is expected to grow over the next few years (34% predicted for 2025). The growing demand for energy in the United States can be seen in Figure 1.1 [2]. Consumption of energy has steadily increased over the last 60 years.

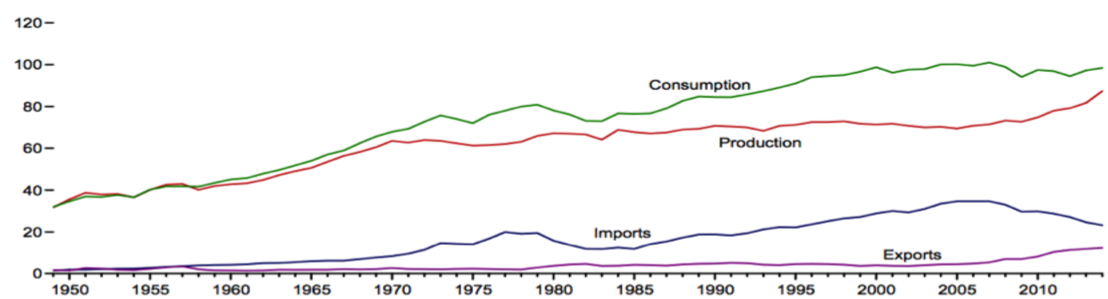

Figure 1.1: Energy Consumption and Production in the United States (Quadrillion BTU) 1949-2014 [2]

Figure 1.2 depicts the energy consumption by source in the United States [2]. As seen in Figure 1.2, in the last 10 years, consumption of renewable energy has steadily increased. Figure 1.1 shows that the consumption of energy in the United States has grown over the last 50 years by nearly 40 quadrillion BTU. With the demand for energy increasing, renewable energy sources will continue to be used at higher rates each year. As the installation costs of renewable generation decrease, the incorporation of these sources into the grid is becoming a more viable option [1].

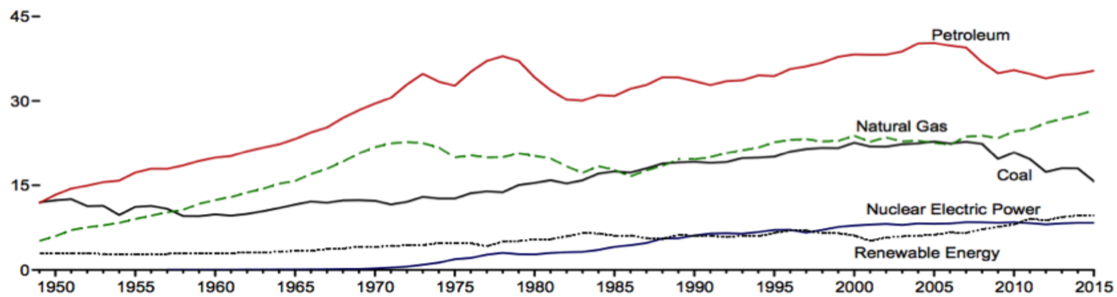

Figure 1.2: Primary Energy Consumption in the United States (Quadrillion BTU) 1949-2014 [2]

While the importance of incorporating renewable generation, such as wind and solar, into the grid is evident, there are many issues preventing full-scale implementation of renewable generation from occurring. Aside from the expense, the main issue that inhibits the incorporation of renewable generation is the variability, uncertainty, and unreliability that renewable sources pose on the grid [6]. Variability can cause voltage collapse, frequency deviations, and instability in system [7–9]. In order to meet the standards set forth by agencies such as the Federal Energy Regulatory Commission and the North American Electric Reliability Corporation, utilities must be able to guarantee that customers receive adequate and quality power, constituting a reliable system. Currently, determining the reliability of a system involving renewable generation is difficult.

Planning for the incorporation of renewable sources into the grid has been studied in [9–11]. In order to meet demand, conventional generators can supply power when renewable generation is unavailable. However, the variability of renewable sources requires that conventional generation be dispatchable at all times. For example, a fast ramping is necessary to compensate for and offset low renewable generation. [6]. In addition to variability, the high uncertainty associated with variable generation can be costly [6]. For instance, weather events with low predictability, such as storms and cloud coverage, forces high ramping in conventional generators [6]. These conventional generators must be ready to supply power or decrease production to maintain a stable system depending on whether the renewable generation suddenly begins to supply power or instantly drops off. If the renewable generation becomes unavailable for several days, this also can cause operational issues [6].

To combat the variability and uncertainty of renewable generation, energy storage has been shown to decrease the stress placed on the grid during peak hours [12–14] and has been used to alleviate variability in renewable generation [15–17]. However, further study is needed to investigate the effects on the reliability of a system involving both renewable generation, such as wind and solar, and energy storage in a micro-grid system.

Therefore, this thesis will investigate the effects on the reliability systems that have both renewable generation and energy storage using a small-scale system called a micro-grid. A micro-grid can be disconnected from the main grid when outages occur.

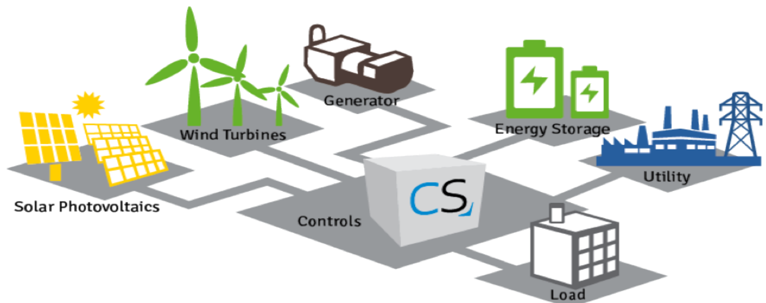

Figure 1.3: Micro-grid System [3]

Figure 1.3 shows the components of a micro-grid system including renewable energy sources and energy storage [3]. The formulated problem assumes a micro-grid system that is functioning in islanding mode. A small-scale IEEE-9 bus test system models the micro-grid, which has three generators and three loads.

System Average Interruption Frequency Index (SAIFI) is used as the reliability metric. According to [18], SAIFI is the simplest reliability measure, the most intuitive to understand, and the index which holds the least counterintuitive surprises. It is perhaps the best single indicator of a distribution system's relative "health" in regards to equipment and design [18]. The goal of this project is to plan for energy storage in a micro-grid considering renewable energy's intermittent nature.

Chapter 2

Literature Review

To improve the reliability of systems with renewable generation, different techniques have been used [1, 19, 20]. In [1], the reliability of the system is shown to have improved when loads are prioritized. The prioritization is implemented using both analytical and simulation demonstrations in a micro-grid system. The micro-grid system contains renewable generation, which were modeled mathematically for both wind and PV generation. Monte-Carlo Simulation was used to evaluate the reliability of an active distribution system with multiple micro-grids. While this study provides a framework for future analysis, the reliability is shown to only improve in prioritized loads while the overall reliability of the system is ignored and other less important demands are left unmet. Most importantly, [1], leaves out energy storage systems in its analysis and does not analyze their impact on reliability. [19] is similar in nature to [1], where the reliability of a system is evaluated that includes renewable generation using Monte-Carlo Simulation. [19] also does not include energy storage in its model and does not prioritze loads. Finally, [20] shows the impacts of a distributed generation (DG) implementation on distribution system reliability using a reliability model and an analytical probabilistic approach. Impacts of different parameters such as the components failure rates, load and DG positions, and DG generation parameters were included in [20]. [1, 19, 20] leave out energy storage in their analysis and results. This thesis will seek to improve upon these results and improve reliability in the overall system by incorporating energy storage systems into a micro-grid system, which will help to meet the demand of the unmet loads.

There have been many methods for modeling wind and PV generation [1, 8, 21–23]. The wind model in [21] uses parameters such as the air density, coefficient of wind energy conversion effeciency, radius of the wind turbine, injection velocity, pitch angle, and nominal power of the turbine. [8] defines four different models for wind turbines based on the type of generator modeling the turbine. In [22], a stochastic approach was used to develop the megawatt resource assessment model of a wind-solar hybrid energy conversion system at any selected location. [23] presents simulation results for the short-circuit current contribution for different types of wind turbine generators obtained through transient analysis using generic wind turbine generation models. This thesis makes use of the wind and solar models used in [1], which predicts generation at different time steps for wind based on a Weibull distribution and for solar based on a Beta Distribution.

As mentioned above, in order to further enhance the reliability of a grid system involving renewable generation, energy storage can be incorporated as a dispatchable source when renewable generation sources are unavailable. Several papers have analyzed methods to model energy storage devices [7, 15, 21, 24–26]. The model used in this thesis is adapted from [26] to account for the power balance requirements and is outlined in Chapter 4.

Power Systems Engineering Research Center (PSERC) has completed several studies that analyze the effects of energy storage and wind generation in grid systems [27], including simulating energy storage in a system with integrated wind resources, modeling and simulating the impacts of storage on the reliability of composite power systems with wind farms, and integrating electric energy storage into a distribution level grid with integrated renewable energy resources. While these projects are beneficial, they focus only on incorporating wind sources and use different metrics to achieve reliability, such as Loss of Load Expectation and Expected Energy Not Served, which are generally not suitable in a distribution system. In addition, the cost function that is optimzed in [27] seeks to reduce annual energy purchasing cost instead of maximizing the reliability. This thesis will improve upon these projects by incorporating two types of renewable generation and formulate a cost function that maximizes the reliability of the distribution system, specifically a micro-grid system.

In analyzing the reliability of a distribution system, several metrics have been developed, including System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Frequency Index (CAIFI). SAIFI is defined as the average frequency of all interruptions per utility customer during the period of analysis [28]. In calculating the SAIFI index, the total number of customer interruptions that occurred in the year is divided by the total number of customers in the system [18]. SAIDI, however, focuses on the average duration of all interruptions per utility customer during the period of analysis. Here, the total customer minutes of interruption are added together and divided by the total number of customers in the system. Finally, CAIFI is the average number of interruptions experienced by customers who had at least one interruption during the period. Other metrices, such as Loss of Load Expectation (LOLE) and Expected Energy Not Served (EENS), are used more often in evaluating the reliability of transmission systems in [18].

This thesis will focus on the reliability of a micro-grid, which is a smart-grid technology expected to provide flexibility and increase efficiency in the future grid system. Micro-grids can disconnect from the main grid, which helps to prevent widespread black outs [29]. Models of micro-grids can be seen in the following references [29, 30]. The IEEE-9 bus test system, a small-scale model of a distribution system, is used in this thesis to provide a micro-grid.

In conducting capacity and voltage regulation simulations, different time steps from 15 minute to one-hour intervals are used [15]. However, according to [15] in order to evaluate the fluctuation in renewable generation and charging profile of energy storage systems, time step sizes of one minute or less may be necessary. Evaluation of frequency control of micro-grids and performance during transient disturbances may require dynamic analysis in intervals ranging from seconds down to microseconds [15]. In order to simplify the problem, an hourly time-step is used in this thesis. While this large of a time-step may result in missing some of the transients that occur in the system, it is believed that the model and simulation results provided in this thesis establish a framework for future work and show the general trends of reliability improvement.

Chapter 3

Methods/Technical Approach

In a micro-grid that is not connected to the main grid, renewable energy is the only source of generation. Due to the renewable generation's intermittency, the power generated is time-varying. In order to maintain the frequency in the micro-grid, demand must be balanced with generation. A mathematical model is developed that has a goal of maximizing the reliability of the system while meeting the demand constraints and operating within the system's limits. The mathematical model is a mixed-integer program that maximizes the reliability of the system by determining the number of critical and non-critical loads that can be satisfied at each time step. The maximization of the number of loads is constrained by the available generation in the system at each specific time step. The software Gurobi with CVX using MATLAB is used to solve the optimization problem and analyze the results. The System Average Interruption Frequency Index (SAIFI) is calculated for the micro-grid system. Systems with and without energy storage are compared and analyzed.

In conducting the simulation, the mathematical model is solved using the branch and bound method, and a one hour time step is used. The length of the study is one day or 24 time steps. These results can be extrapolated for one week. Based on the solar radiation and wind speeds during a specific time of year, this model can be adjusted and scaled to increase the length of the study. Static analysis is used to study and analyze the reliability of a system. In most reliability studies, a steady-state or a static model is used [15]. However, with the inclusion of energy storage in the system, a dynamic model would more accurately analyze the transient phenomena. When the time constant used is too large in relation to when and how long an event occurs, then the dynamic model can be used to accurately analyze the event [15]. This work focuses on using a static model with a large time constant; however, the future work would include a dynamic model with a smaller time constant.

In the first 4 cases, the system uses two wind turbines, two solar panels, 450 critical loads, and 250 non-critical loads [1]. The rated power for each wind turbine and solar panel is 2000kW. The rated power for each critical load is 10kW and for each non-critical load is 4kW [1]. The rated power for the energy storage is 400kW. Power losses are assumed to be negligible in all five cases.

In the first 2 cases, a topology is not used and the capacity on the lines are assumed to be infinite. The next 2 cases make use of the IEEE-9 Bus System, and the capacity on the lines are constrained as specified in the MATPOWER description [31].

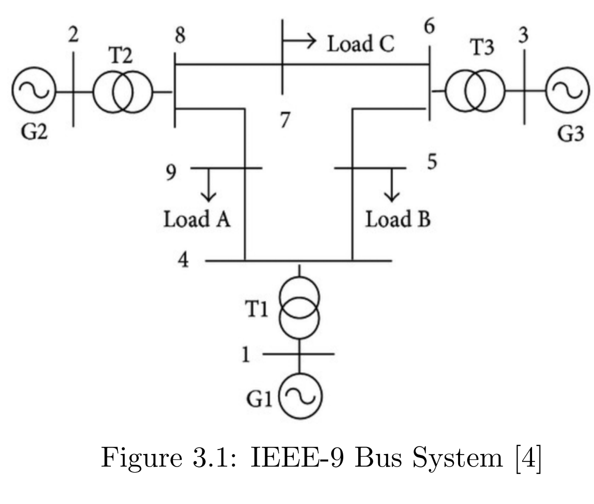

Figure 3.1: IEEE-9 Bus System [4]

Figure 3.1 shows the IEEE-9 bus system [4].

Chapter 4

Modeling Renewable Energy Sources in the Micro-grid

4.1 Wind Power Generation Model

$F_w(v)$ is the cumulative probability distribution for the wind speed, which is shown in (4.1). Wind generation is shown to fit a Weibull distribution [1]. c is the scale parameter, and k is the shape parameter, which are defined for a certain region in [1]. These values are derived from historical data in [32] and shown in Table 4.1.

$$F_w(v) = 1 - e^{-(v/c)^k} \tag{4.1}$$

In order to determine v, the wind speed values in (m/s) for a required duration, the inverse transformation method is implemented [33]. The inverse transformation method states that if a random variable (in this case v) follows the $U[0,1]$ uniform distribution, then the random variable $X = F^{-1}(U)$ has a continuous cumulative probability distribution function $F(X)$. Based on this principle, (4.2) shows that v is

Table 4.1: Weibull Distribution Data [1]

Parameter	Region 1
Mean speed (m/s)	7.0
k	2.62
c	7.88

the simulated wind speed in (m/s) based on X, the random variable in the uniform distribution, where X is a random value between 0 and 1. The power generated from wind energy is based on the wind speed, which is outlined in (4.4). Twenty-four simulated wind speeds are obtained by generating a random variable X at each time step. These wind speeds are used to calculate the P_{WTGMax}, the power from the wind energy in (kW).

$$v = c[-ln(1-X)]^{1/k} \tag{4.2}$$

P_{WTGMax} is generated for each time step by examining the wind speed v at each time step as seen in (4.4). P_{WTGMax} contains 24 values showing the maximum available wind power at each of the 24 time steps. P_{WTGMax} is calculated using values a and b, which are formulated in [1] and shown in (4.3).

$$a = \frac{P_{rated}}{v_{rated}^3 - v_{cut-in}^3} \tag{4.3}$$

$$b = \frac{v_{cut-in}^3}{v_{rated}^3 - v_{cut-in}^3} \tag{4.4}$$

$$P_{WTGMax} = \begin{cases} 0 & 0 < v \leq v_{cut-in} \\ av^3 - bP_{rated} & v_{cut-in} < v \leq v_{rated} \\ P_{rated} & v_{rated} < v \leq v_{cut-out} \\ 0 & v_{cut-out} \leq v \end{cases} \tag{4.5}$$

v_{rated} is the speed in (m/s) at which the maximum power can be produced from the wind turbine. P_{rated} is the maximum power in (kW) that can be produced by

Table 4.2: Wind Turbine Data [1]

Parameter	Region 1
Rated Power (kW)	2000
Rated Speed (m/s)	15
Cut-in speed (m/s)	3
Cut-out speed (m/s)	25

the wind turbine at the rated wind speed. v_{cut-in} is the minimum wind speed in (m/s) required to produce the power from the wind turbine. $v_{cut-out}$ is the maximum speed in (m/s) at which the wind turbine can operate. These values that are used in cases 1-4, are outlined in Table 4.2, and obtained from the wind turbine manufacturer in [1].

4.2 PV Power Generation Model

Calculating the power generated from solar panels depends on the amount of solar radiation and the temperature [1]. [1] uses solar radiation to determine the power output of solar panels. Historical data of solar radiation ranging over five years was gathered from NASA's Atmospheric Science Data Center [34] and fitted to a beta distribution [35]. The probability distribution function of the beta distribution is given in (4.6). Twenty-four solar radiation values (g values) are simulated using the beta distribution function in MATLAB and utilized to find the solar power output at each of the 24 time steps.

$$g(x) = \frac{x^{(\alpha-1)}(1-x)^{(\beta-1)}}{B(\alpha,\beta)} \tag{4.6}$$

where, B in terms of the gamma function (Γ) is defined in (4.7) as:

$$B(\alpha,\beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)} \tag{4.7}$$

Table 4.3: Solar Panel Data [1]

Parameter	Region 1
Rated Power P_{sn} (kW)	2000
Standard Solar Radiation $G_{std}(W/m^2)$	1000
Radiation Certain Point $R_c(W/m^2)$	150

The α and β, shown in (4.8) and (4.9), were calculated in [1] using statistics and MATLAB's machine learning toolbox.

$$\alpha = 1.03745 \tag{4.8}$$

$$\beta = 1.38279 \tag{4.9}$$

The solar power output in (kW), P_{PVMax}, is defined in terms of solar radiation. It is developed in [36] and given in (4.10):

$$P_{PVMax} = \begin{cases} P_{sn}\frac{g^2}{G_{std}R_c} & 0 \leq g < R_c \\ P_{sn}\frac{g}{G_{std}} & R_c \leq g \leq G_{std} \\ P_{sn} & g > G_{std} \end{cases} \tag{4.10}$$

g is the solar radiation in (W/m^2) simulated in (4.6). G_{std} is the solar radiation in the standard environment and is usually set to 1000 W/m^2 according to [1]. R_c is a certain radiation point and is usually set to 150 W/m^2 [1]. P_{sn} is the rated output power of solar panels and is 2000kW for cases 1-4.

4.3 Energy Storage Model

There are several different control strategies for modeling the energy storage [15]. **Static Mode:** The storage element model is set to either charging or discharging at specific rates. A partial planning picture is shown, but it does not reveal issues that are exposed through time-series simulation [15].

Time Mode: The storage element is scheduled to charge and discharge at specific times of day at a constant level [15].

Peak Shave Mode: The storage element is set to discharge when the load at a substation exceeds a certain peak value. At this time, the storage attempts to produce sufficient power to alleviate the stress on the grid to meet the demand [15].

Load Following Mode: The storage element discharges at a specified time predicted through a short-term load forecast when it will be necessary to offset load demand. [15].

Loadshape Following Mode: The storage element charges and discharges according to a predefined shape. This capability gives the planner the flexibility to investigate many different scenarios without requiring hard-coded computer algorithms to be implemented in the planning tools. [15].

Dynamics Mode: Modeling fast-charging phenomena such as frequency control of micro-grids or fault current contributions is possible using this mode. [15].

Examples of these simulation modes are available in the open-source OpenDSS software [15]. The dynamics mode examples can be seen in [15], [7], and [37].

According to [15], static analysis is currently an adequate method for evaluating storage applications on distributions; however, in the future when energy storage systems become more prevalent, then sequential-time simulation will be required for more accurate results.

The control method used in this thesis allows for the charge of the storage system, in this case a battery, when there is a surplus of generation in the system. The battery supplies energy when it is available and when there is an inadequate amount of generation in the system.

[26] presents in (4.11) an energy storage model using the state of charge (SOC) of the battery.

$$E_{ES}(t) = \begin{cases} 0 & SOC = 0 \\ \int_0^t P_{ES}(t)dt + E_{ES,rated}SOC(t) & 0 < SOC < 1 \\ E_{ES,rated} & SOC = 1 \end{cases} \tag{4.11}$$

SOC is a value between 0 and 1. E_{ES} is the available energy stored at time instance t in (kWh). $E_{ES,rated}$ is the rated energy that can be stored by the battery in (kWh). $P_{ES}(t)$ is the power produced by energy storage at time t in (kW). The SOC is the available energy stored at time t divided by the rated energy that can be stored, shown in (4.12).

$$SOC(t) = \frac{E_{ES}(t)}{E_{ES,rated}} \tag{4.12}$$

In this study, the energy storage model shown in below is used and calculates the maximum amount of energy available at the next time step based on the current amount of generation, demand, and available energy storage. This model assumes that the generation that is leftover after meeting the demand is stored in the battery. If generation is not leftover and there exists unmet loads, then the model dispatches the energy storage to supply power to the loads. $E_{ESMax}(t)$ is the maximum available energy stored at time step t.

$$E_{ESMax}(t+1) = E_{ESMax}(t) - P_{ES}(t)\Delta t +$$
$$(P_{WTG}(t) + P_{PV}(t) + P_{ES}(t) - \sum\nolimits_{i \in \mathcal{N}_i} x_i L_i - \sum\nolimits_{j \in \mathcal{N}_j} y_j L_j)\Delta t$$
$$E_{ESMax}(1) \leq \overline{E_{ES}}$$

$$E_{ESMax}(1) = \overline{E_{ES}} \tag{4.13}$$

$\overline{E_{ES}}$ is the rated maximum energy of energy storage. The model assumes that initially the battery is charged, so the maximum stored energy at time 1 or 12AM is equal to the rated maximum energy (4.13).

Since, $E_{ESMax}(t)$ is in (kWh), and a one hour time step is used, then the maximum energy stored at time t ($E_{ESMax}(t)$), is equal to the maximum power stored at time t ($P_{ESMax}(t)$) in (kW). If in the future different units or a different time step are used, then the model presented in (4.10) and (4.11) can be used.

4.4 Critical and Non-Critical Load Model

To obtain a time-varying residential load model, OpenDSS is used to obtain 24 per unit values. This residential load profile is scaled to (kW) based on the rated power for critical loads and non-critical loads. Based on [1], the rated power for the critical loads is set to 10kW and the rated power for the non-critical loads is set to 4kW.

Chapter 5

Optimization Formulation

This model was adapted from [19] and used for cases 1 and 2. Twenty-four time steps t are used, so T is the time period for one day. The cost function seeks to maximize the number of loads. x_i is a binary vector showing the number of critical loads that are met at each time step. y_j is a binary vector showing the number of non-critical loads that are met at each time step. If x_i and y_j is a 1, then the load i and j has been met at the specific time step. ω_1 is the importance metric of meeting the critical loads and is set to 100. ω_2 is the importance metric of meeting the non-critical loads and is set to 50. ω_3 is the cost of using energy storage and is set to 10. These values were chosen arbitrarily, but can be altered as long as ω_1 is greater than ω_2.

$$\begin{aligned}
\max \quad & \sum\nolimits_{t=0}^{T} (\omega_1 \sum\nolimits_{i \in \mathcal{N}_i} x_i L_i + \omega_2 \sum\nolimits_{j \in \mathcal{N}_j} y_j L_j - \omega_3 P_{ES}(t)) \\
\text{s.t} & \sum\nolimits_{i} x_i L_i + \sum\nolimits_{j} y_j L_j \leq P_G(t) \\
& P_{WTG}(t) + P_{PV}(t) + P_{ES}(t) = P_G(t) \\
& 0 \leq P_{WTG}(t) \leq P_{WTGMax}(t) \\
& 0 \leq P_{PV}(t) \leq P_{PVMax}(t) \\
& 0 \leq P_{ES}(t) \leq P_{ESMax}(t)
\end{aligned}$$

$$\omega_1 > \omega_2$$

$$x_i \in \{0,1\}$$

$$y_j \in \{0,1\}$$

$$P_{ES} \in \Re$$

$$nloads = |\mathcal{N}_i \cup \mathcal{N}_j|$$

$$E_{ESMax}(t+1) = E_{ESMax}(t) - P_{ES}(t)\Delta t +$$

$$(P_{WTG}(t) + P_{PV}(t) + P_{ES}(t) - \sum_{i \in \mathcal{N}_i} x_i L_i - \sum_{j \in \mathcal{N}_j} y_j L_j)\Delta t$$

$$E_{ESMax}(1) \leq \overline{E_{ES}}$$

The loads are specified based on a load profile obtained in the *Critical and Non-Critical Load Model* section in Chapter 4. L_i is a vector showing the power demand of each critical load values in (kW). There are i number of critical loads and is set to 450 for cases 1 and 2. L_j is a vector showing the power demand of each non-critical load values in (kW). There are j number of non-critical loads and is set to 250 for cases 1 and 2. n_{loads} is the number of all of the loads that must be met by the system and is 700 for cases 1-4. $\mathcal{N}_i$ is the set of critical loads. $\mathcal{N}_j$ is the set of non-critical loads.

The decision variables include the power produced by each source and the energy stored at each time step. $P_{WTG}(t)$ is the wind turbine generation decision variable at time step t (kW). $P_{PV}(t)$ is the solar generation decision variable at time step t (kW). $P_{ES}(t)$ is the energy storage generation decision variable at time step t (kW). $P_G(t)$ is the total power generation decision variable at time step t (kW) and is set to be the sum of the available generation in the system.

The optimization problem is constrained by the available generation and storage seeking to meet the specified loads. The maximum available energy storage generation at time step t is $P_{ESMax}(t)$ and is initially set to 400kW. The rest of the values for the time period are calculated and chosen based on the formulation in Chapter 4, which is used in the optimization problem. $E_{ESMax}(t)$ is the maximum available energy stored at time step t and is initially set to 400kWh. $P_{PVMax}(t)$ is the maximum available solar power at time step t and is simulated in Chapter 4. $P_{WTGMax}(t)$ is the maximum available wind power at time step t and simulated in Chapter 4.

$$\text{SAIFI} = \frac{\sum_{i \in \mathcal{N}_i} x_i + \sum_{j \in \mathcal{N}_j} y_j}{nloads} \tag{5.1}$$

(5.1) shows the System Average Interruption Frequency Index that is calculated based on the number of loads met in solving the optimization problem. SAIFI is the number of loads met divided by the total number of loads.

For cases 3 and 4, the IEEE-9 bus topology, which has nine lines and nine nodes, is introduced along with the line capacity constraints. DC Power flow is used in these cases. The line capacity was limited to 2500kW for each line. 225 critical loads are placed at nodes 5 and 9. 250 non-critical loads are placed at node 7. Two wind turbines are placed at node 2. Two solar panels and 1 energy storage system are placed at node 3. Node 1 is used as a slack bus. The following decision variables are introduced into the above system. $P_{injection}(node, t)$ is a vector showing the power injection defined at each $node$ for each time step t. θ is the voltage angle at each $node$. Pf is the power flow on each line. $Line_{capacity}$ is the limit of each line in kW, which is set to 2500kW for each line. $\sum_{k \in \mathcal{N}_k} z_k L_k$ is the total load placed at node 7.

$\sum_{j \in \mathcal{N}_j} y_j L_j$ is the total load placed at node 5. $\sum_{i \in \mathcal{N}_i} x_i L_i$ is the total load placed at node 9.

Additional parameters are introduced and needed to calculate the above decision variables. B is the admittance matrix for the IEEE-9 bus topology. B is calculated using the Adjacency and Degree matrices. $\overline{B}$ is the adjusted matrix so the inverse of B can be taken. b is the admittance in each node of the IEEE-9 bus topology. F is the constructed matrix that determines the appropriate sign for each voltage angle.

The following constraints are introduced into the model shown in (5.2)-(5.10).

$$P_{injection}(1) = 0 \tag{5.2}$$

$$P_{injection}(2) = P_{WTG} \tag{5.3}$$

$$P_{injection}(3) = P_{ES} + P_{PV} \tag{5.4}$$

$$P_{injection}(4) = 0 \tag{5.5}$$

$$P_{injection}(5) = -\sum_{j \in \mathcal{N}_j} y_j L_j \tag{5.6}$$

$$P_{injection}(6) = 0 \tag{5.7}$$

$$P_{injection}(7) = -\sum_{k \in \mathcal{N}_k} z_k L_k \tag{5.8}$$

$$P_{injection}(8) = 0 \tag{5.9}$$

$$P_{injection}(9) = -\sum_{i \in \mathcal{N}_i} x_i L_i \tag{5.10}$$

The equations (5.11) and (5.12) are used to find the Power Flow.

$$\theta = \overline{B}^{-1} P_{injection}(2:9) \tag{5.11}$$

$$Pf = diag(b) F \theta \tag{5.12}$$

The last constraint (5.13) restricts the line capacity.

$$-Line_{capacity} <= Pf <= Line_{capacity} \tag{5.13}$$

Chapter 6

Results

The reliability of the system is improved or maintained in all time steps when energy storage is included in the micro-grid. For each time step, the available generation is shown on the left and the critical and non-critical loads that can be satisfied are shown on the right.

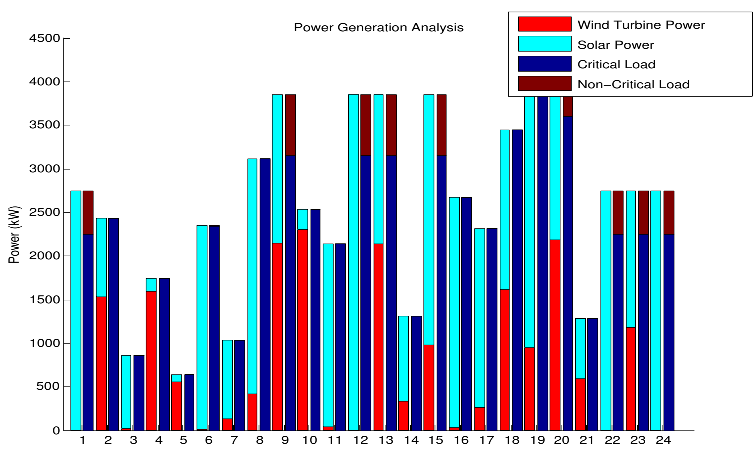

Figure 6.1: Case 1: Generation Analysis without Energy Storage

Figure 6.1 shows the results from case 1, which does not include energy storage or a topology. In this case, the power is balanced between the load and generation because excess power is not needed to charge the battery. The only available generation comes from the wind and solar energy.

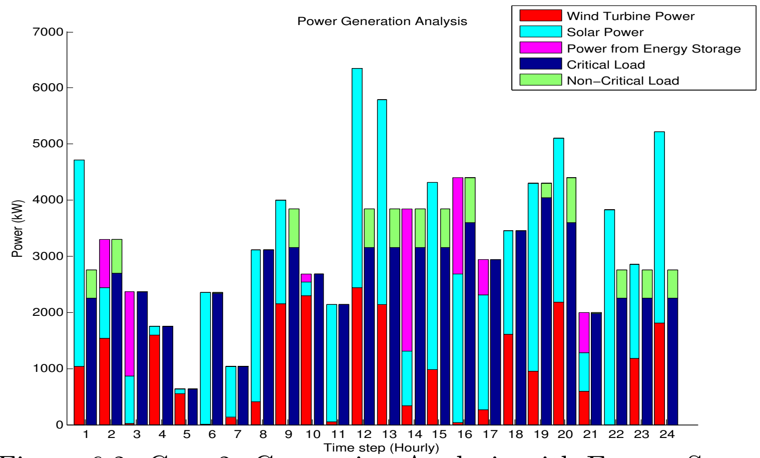

Figure 6.2: Case 2: Generation Analysis with Energy Storage

Figure 6.2 shows the results from case 2, which describes a system that includes energy storage, but it does not use a topology. The results show the available generation, critical, and non-critical loads at each time step. In this case, the power is not balanced with the loads because the excess generation goes into charging the battery. When comparing case 1 and case 2, it is shown that the energy storage helps to meet more demand and compensate for the lack of adequate power in some of the time steps, particularly in time steps 2, 3, 14, 16, 17, and 21 which correspond to 1AM, 2AM, 1PM, 3PM, 4PM, and 8PM. Particularly at peak times such as 3PM, 4PM, and 8PM, these results are significant since the energy storage can help to offset the demand and relieve stress placed on the renewable generation. This translates to a more reliable system as seen in Table 6.1. The SAIFI index at these time steps increase from case 1 to case 2, thereby showing an improvement in reliability of the system. For example, at 3PM, the system without energy storage showed a reliability index of 0.479, but in case 2 where a system with energy storage is examined, the SAIFI index is 1, which corresponds to the highest achievable reliability standard. In addition, the reliability at 1PM increases from 0.269 in case 1 to 1.0 in case 2.

Table 6.1: SAIFI Indices

Time Step	Case 1	Case 2	Case 3	Case 4
12AM	1	1	1	1
1AM	0.581	1	0.581	0.724
2AM	0.206	0.564	0.206	0.207
3AM	0.417	0.417	0.417	0.417
4AM	0.151	0.153	0.151	0.153
5AM	0.561	0.561	0.576	0.576
6AM	0.213	0.214	0.213	0.214
7AM	0.556	0.556	0.657	0.657
8AM	1	1	1	1
9AM	0.517	0.549	0.517	0.517
10AM	0.436	0.437	0.436	0.437
11AM	1	1	1	1
12PM	1	1	1	1
1PM	0.269	1	0.269	0.269
2PM	1	1	0.976	0.976
3PM	0.479	1	0.539	0.539
4PM	0.414	0.527	0.414	0.416
5PM	0.493	0.494	0.493	0.493
6PM	0.743	0.743	0.809	0.809
7PM	1	1	1	1
8PM	0.307	0.476	0.307	0.307
9PM	1	1	0.947	0.947
10PM	1	1	1	1
11PM	1	1	1	1

Another example of this is shown at 8PM when the reliability index improved from 0.307 in case 1 to 0.476 in case 2.

Figure 6.3 shows the generation and load balance in case 3, which describes an IEEE-9 bus system that does not include energy storage. The power supplied by the wind and solar energy is the only generation available in the system. Because power flow constraints are placed on the lines in the system, fewer loads can be met, and the reliability of the system is decreased from case 1. This can be seen at 2PM and

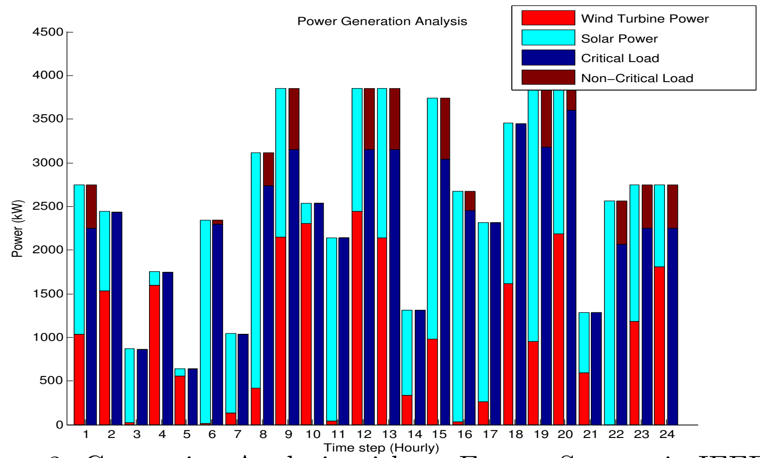

Figure 6.3: Case 3: Generation Analysis without Energy Storage in IEEE-9 Bus System

9PM where the reliability indices in case 1 are both 1, but are 0.976 and 0.947 in case 3 respectively.

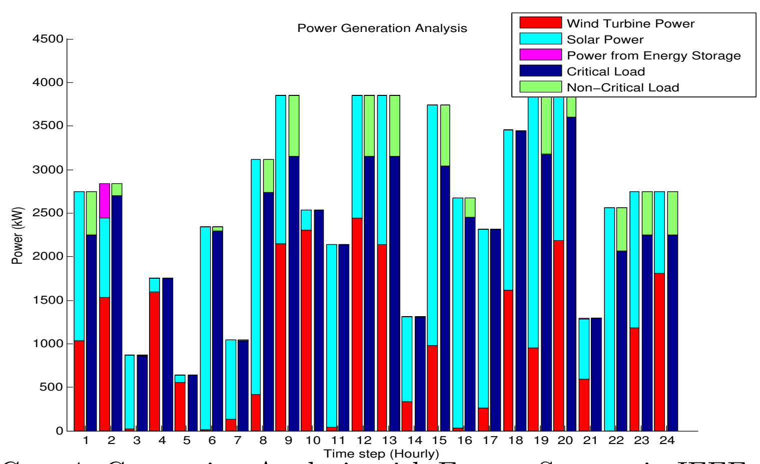

Figure 6.4: Case 4: Generation Analysis with Energy Storage in IEEE-9 Bus System

Figure 6.4 shows the generation and load balance in case 4, an IEEE-9 bus system that includes energy storage. The only use of energy storage is seen at time step 2, which corresponds to 1AM, because the system is constrained by the power flow. The generation produced by the wind and solar sources cannot supply the loads and charge the battery while remaining within the power flow line capacity restrictions.

Thus, the only improvement in reliability from case 3 to case 4 is at time step 2 or 1AM when the reliability index increases from 0.581 to 0.724.

Therefore, the improvement in the SAIFI reliability index is limited in cases 3 and 4, which are shown in Figure 6.3 and 6.4 respectively, because of the restriction on the power flow in the IEEE-9 bus topology. However, energy storage does slightly improve the reliability in case 4. The potential to increase the reliability indices exist if the line capacities are increased and if the number of storage systems are increased.

Chapter 7

Honduras Case Study 5

This research project was inspired by my participation in the Montana de Luz project in 2014, in which I traveled with Ohio State's College of Engineering to Nueva, Esperanza, Honduras to design, build, and test a small-scale 600W wind turbine. Montana de Luz is an orphanage that provides support for children with HIV and AIDS, and frequently experiences unforeseen power outages due to the instability of the regulating body of the electric grid. In addition, the cost of electricity from the main grid is very expensive.

Using the results from this research, a small test case was built and simulated to show the effects of the renewable generation and energy storage on this system. The results show that energy storage and renewable generation help to offset the orphanage's reliance on the main grid. However, more work will need to be done to incorporate more renewable generation in order to see a drastic change in reliance on the main grid.

In this case, the optimization problem is adjusted because the system is assumed to be connected to the main grid, which can provide a maximum of 12kW of constant power. The loads are not prioritized in this case. The wind and main grid generation are placed on node 2. The solar panels and energy storage system are placed on node

Table 7.1: Wind Turbine Data from Honduras

Parameter	Honduras
Rated Power (W)	600
Rated Speed (m/s)	12
Cut-in speed (m/s)	4
Cut-out speed (m/s)	14

3. The orphanage has an estimated load demand of 12kW. Recently in March of 2017, four 335W solar panels were installed at the orphanage. The line constraint is set to 10kW.

The following revision is made to the model, which eliminates the prioritization of loads and penalizes the use of power from the main grid to meet demand. The power supplied by the main grid, P_{grid}, is a decision variable that is included in the total amount of generation in the system, P_G.

$$
\begin{aligned}
\max \quad & \sum_{t=0}^{T} \Big(\sum_{i \in \mathcal{N}_i} x_i L_i - \omega_1 P_{ES}(t) - \omega_2 P_{grid}(t) \Big) \\
\text{s.t} & \sum_{i} x_i L_i \leq P_G(t) \\
& P_{WTG}(t) + P_{PV}(t) + P_{ES}(t) + P_{grid}(t) = P_G(t)
\end{aligned}
$$

The specifications for the installed wind turbine at Montana de Luz is obtained from the manufacturer and shown in the table. There is one 600W turbine, four 335W solar panels, and one energy storage system battery. The current system in Honduras does not include a battery, however, this study includes a battery to examine the benefits that a battery with a rating of 14kW can supply to the system.

Figure 7.1 shows the results of the power balance between the loads and available generation. The results indicate the need for increased renewable generation and energy storage systems if a significant impact is going to be seen in achieving independence from the main grid. The energy storage is only able to be dispatched at time steps 8 and 9, which correspond to 7AM and 8AM because of the line capacity restrictions. However, this incorporation of storage does help to reduce the reliance of the orphanage on the main grid. The SAIFI index shows that the system is mostly reliable. The exception exists at peak times such as at 5PM and 6PM where the assumed line capacities restrict the delivery of power to the loads.

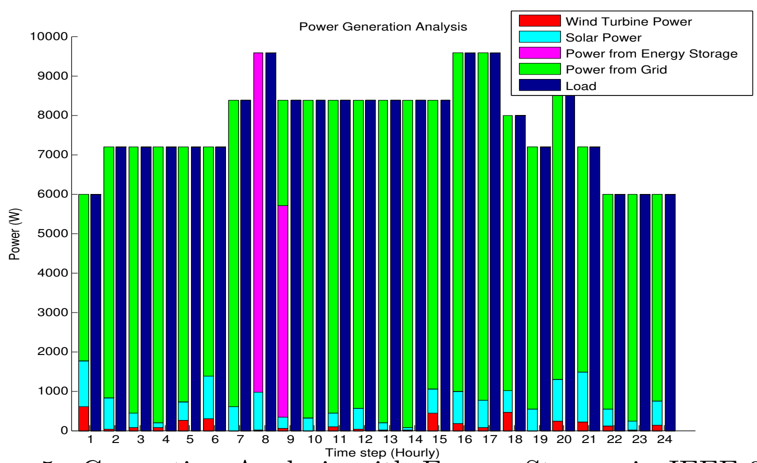

Figure 7.1: Case 5: Generation Analysis with Energy Storage in IEEE-9 Bus Honduran System

Renewable generation and energy storage is costly; however, it is believed that their long-term benefits, which include the free use of energy, and environmentally friendly impact, significantly outweigh the capital improvement and initial installation cost.

While the scope of this project was on a small-scale rural system in Honduras, this approach can be applied to other systems locally and internationally assuming that the rated wind speed and solar radiation data is available. A study similar in nature is seen in [38].

Table 7.2: SAIFI Index of Honduran System

Time Step	Case 5
12AM	1
1AM	1
2AM	1
3AM	1
4AM	1
5AM	1
6AM	1
7AM	1
8AM	1
9AM	1
10AM	1
11AM	1
12PM	1
1PM	1
2PM	1
3PM	1
4PM	1
5PM	0.666
6PM	0.666
7PM	1
8PM	1
9PM	1
10PM	1
11PM	1

Chapter 8

Conclusion

This thesis shows that the reliability of a micro-grid system functioning in islanding mode that includes renewable generation improves with the incorporation of energy storage. The simulated results of the optimization problem demonstrate the improvement of the reliability of the system at specific time steps when energy storage is included. These time steps include peak times when demand is increased, such as at 3PM, 4PM, and 8PM. When a topology is included in the system and line capacities are placed on the system, the improvement in reliability is reduced. However, the reliability is still improved when energy storage is included as shown in case 4. As seen in the Honduran case study, these findings can be applied to many different distribution systems worldwide. The results show that reliability is improved when energy storage is incorporated; however, either a combination of more energy storage systems and renewable generation or traditional generation will need to be used to obtain a fully reliable system. Incorporating more energy storage systems and renewable generation may be seen as too costly, so traditional readily dispatchable generation may be preferred, but the advantages of renewable generation and energy storage systems include the long-term cost effectiveness of the system as installation costs decrease and eco-friendly impacts on the environment. In the future, this study can be expanded to include more loads and include more types of renewable generation as well as storage systems. Experimenting with the different combinations of renewable generation and energy storage systems might indicate the exact sizing and capacity needed. In the future, power losses should be taken into consideration and a smaller time step should be used to investigate the variability of the renewable generation and loads.

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